

1 **Applying a New Systematic Fuzzy FMEA Technique for Risk**

2 **Management in Light Steel Frame Systems**

3 **Abstract:**

4 Light Steel Frame (LSF) system is mainly used for construction of short and intermediate-
5 height buildings in developed countries whereas considerable heed is not given to it in
6 developing countries. Unfamiliarity to LSF risks is one of the main reasons for this averseness
7 so risk management can remedy this challenge and develop application of the LSF. Hence, this
8 paper investigates the risk management of LSF system considering design, construction and
9 operation phase. Three main steps entailing risk identification, assessment and responding
10 using fuzzy Failure Mode and Effect Analysis (FMEA) technique are suggested for risk
11 management implementation and for validation of responses, a novel index with respect to
12 weighted combination of project quality, time and cost are calculated. The methodology is
13 demonstrated on a pilot study in a developing country. By using interview, 29 significant risks
14 are extracted in design, construction and operation and then evaluated by proposed fuzzy
15 method. Results showed that the share of the risks in these steps are 21%, 31% and 48%
16 respectively. The results revealed that the risks in the construction and operation phases are
17 higher than those in the design phase. The results also show that involving safety as a project
18 object in the risk management process could eventuate acceptable results.

19
20 **Keywords:** Fuzzy FMEA; Light Steel Frame system; Project Life Cycle; Risk classification;
21 Risk identification; Risk management; Risk response strategy.

22 **1 Introduction**

23 The Light steel frame (LSF) is a load bearing wall system made of cold-formed steel sections
24 (CFS) and has various applications in the construction industry, such as short, intermediate
25 building and extra-floor residential houses or apartments. LSF Components are made of CFS
26 sheets with thicknesses varying from 0.45 to 2.45 mm and protected against rust and corrosion
27 by using zinc alloys (Schafer, 2011). The load bearing elements consist of single or combined
28 sections, mainly consisting of C or U shape or their combination. The walls are formed by the
29 arrangement of the vertical components of the U shape sections (studs), which are restrained
30 from above and below inside the horizontal U shape components (runner or track). The roof of
31 the last floor is often sloped and made of CFS load-bearing members called “joists” and the
32 track is typically referred to as the “rim joist”. Connections in LSF are usually cold and made
33 with automatic screws, despite that other connections such as rivets and welding are used in
34 special cases (Soares, et al., 2017).

35 LSF system has multiple advantages including high speed construction, low weight of building,
36 resistance against earthquake and insect damage, almost 100% recyclability, economical usage
37 of energy , the easiness of maintenance and repair, possibility of modular construction and pre-
38 construction of panels, the comfortable construction of mechanic and electric equipment,
39 excellent thermal insulation, designability of various external views by request of employer
40 and adapted with architectural concept, long lifespan, quick return of initial capital investment,
41 adapted with environment, durability and stability of the structure and increase the net area
42 (Soares, et al., 2017). In contrast, LSF system has some disadvantages such as low resistance
43 of wall insulation core against fire, complexity of thermal bridge modelling due to several
44 types of materials, weakness against sever wind, the lack of expert and labour force, unknown
45 structural behaviour of the system, higher prices than traditional materials in countries that
46 have not yet developed this system and height limitation (Jatheeshan and Mahendran, 2015,
47 Soares, et al., 2014).

48 Having been appeared in the early 20th century, most likely to mimic the dimensioned wood
49 houses become the common construction method for shelter, LSF system grew rapidly in
50 Europe. Also, destruction of buildings during the world war II was caused shortage of homes
51 in several countries such as Germany, Japan, France and hence LSF was one of the best
52 alternatives to meet this demand (Yu, 2016). Although the origin of LSF system was rooted in
53 shortage of building materials, environmental concerns and introducing an alternative option
54 for wood frame building, the mentioned advantages turned LSF constructions to a reliable

55 option for construction industry in developed countries and one of the most popular system in
56 dry (i.e. prefabricated) construction category (LSK, 2007).

57 In contrast to developed countries, this approach was not clearly embraced in developing
58 countries such as Iran, Malaysia, South Africa and China (Dosumu and Aigbavboa, 2018,
59 Mahdavinejad, et al., 2012, Saikah, et al., 2017, Shi and Yu, 2009). Lack of information in
60 practitioners, clients, engineers, project managers and other related experts about the LSF risks
61 and proper strategies for dealing with them is one of the main reasons for failure to expand the
62 LSF system in the construction industry (Luo, 2015). Similarly, the investigation in Australia
63 and some cases in Italy and Mediterranean countries as a matter of successful examples also
64 implies that the LSF system should be coordinated with consumers' culture (Celik and Kamali,
65 2018, Franklin, et al., 2020). It was found that having more knowledge and experience about
66 the LSF system dampens its current risks. Therefore, this paper aims to recognize the relevant
67 risks in LSF structures and appropriate strategies to respond during design, construction and
68 operation steps. To deal with this problem in a systematic approach, we intend to employ risk
69 management procedure in LSF buildings in developing countries.

70 Accordingly, a comprehensive framework for investigation of LSF risks is provided here and
71 this paper aims to increase the understanding and knowledge about the LSF system for
72 engineers, managers, employers and other related people by applying the risk management to
73 enhancing the chance of using this alternative building system. This framework entailing
74 identification, assessment and responding to each risk event is defined in a way that it could be
75 employed in similar problems and case studies.

76 This paper organises as follows: Firstly, a literature review of the works investigating the LSF
77 risks and risk management in construction industry are given in the next section. The proposed
78 framework steps are then introduced. The results and discussion are also represented in forth
79 section. Finally, the conclusions are drawn and some recommendations are made for future
80 studies.

81

82 **2 Literature review**

83 **2.1 LSF systems**

84 Despite a plethora of research works conducted on structure of LSF system, there is not any
85 specific research focused on the risk management in LSF system. Some sporadic researches
86 such as Shi and Yu (2009), Barnard (2011), Eren (2013) and Saikah, et al. (2017) have focused
87 on risk identification of LSF system but not as comprehensive as one could be considered them

88 as risk management procedure. In a similar manner, [Dosumu and Aigbavboa \(2018\)](#)
89 investigated adopting LSF system in South Africa by considering risk identification and
90 evaluation and reviewing challenges and solutions, but had not presented a specific framework
91 for risk management. [Franklin, et al. \(2020\)](#) have also conducted an on-line survey for
92 evaluation of structural resistance, construction time and cost and acoustics responses of LSF
93 buildings and suggested some modifications on the LSF system.

94 Some researches focused on a specific aspect of the system. For example, [Veljkovic and](#)
95 [Johansson \(2006\)](#) introduced the LSF systems as a dry construction system and studied the
96 manufacturing industry in Sweden by examining ways to reduce production costs in a
97 recession. Researchers also investigated the LSF technology for economic housing in
98 developing countries such as Iran and China and concluded that LSF system can be economic
99 for these countries ([Li, et al., 2014](#), [Mahdavinejad, et al., 2012](#), [Noorzai and Golabchi, 2020](#)).

100 Some modifications in construction of the system were also provided by [Darcy and Mahendran](#)
101 [\(2008\)](#) and [Schafer \(2011\)](#). Suggestions of these papers can be useful in energy efficient and
102 affordable architectural concept of LSF system. A multidimensional comparison between
103 reinforced concrete and LSF buildings was also made in Mediterranean countries and Iran
104 ([Celik and Kamali, 2018](#), [Zeynalian, et al., 2013](#)). It has been proofed that using of LSF system
105 allows a great improvement in cost, quality, time and earthquake related risks.

106 Some LSF related researchers analysed sustainable performance of LSF system with the main
107 focus on environmental and energy saving aspects. [Fallah \(2005\)](#) found steel and its derivatives
108 are a very appropriate option with respect to sustainable development. For the energy saving
109 subject see for example [Soares, et al. \(2014\)](#), [Santos, et al. \(2014\)](#), [Soares, et al. \(2017\)](#) and
110 [Steau and Mahendran \(2020\)](#). They suggested strategies such as changing the insulation core,
111 using of modern construction methods that optimize heat exchange transference and double
112 plasterboards for reducing thermal bridges and for improving the thermal resistance of LSF
113 envelope elements. Similar to [Trevathan and Pearse \(2008\)](#), [Paul, et al. \(2015\)](#) analysed the
114 sound insulation coefficient in LSF walls. They tested materials such as cement and plaster
115 boards, smart resin, PVC and polymer mortar covered XPS panels as a matter of insulation
116 core. Besides, they examined the effect of using the sealing strip between panels and sub-
117 runners.

118 Safety-related researches in this field was devoted to experimental and numerical studies for
119 analysing the resistance of LSF system against fire and earthquake. For example, [Jatheeshan](#)
120 [and Mahendran \(2015\)](#) examined the fire resistance of LSF walls by finite element method and
121 real experiments on constructed specimens. In their research, they have confirmed the high

122 ability of the finite element method to model and demonstrate the performance of these
123 structures subjected to fire. We can conclude from this research and other similar not mentioned
124 papers that using of incombustible materials in insulation core of the walls significantly reduce
125 the ignition risk.

126 Regarding seismic behaviour and structural analysis, it is shown that LSF system in
127 combination with shear walls can be considered as an appropriate choice in areas with high
128 seismic hazards or high important buildings like schools and hospitals based on experimental
129 researches of [Fiorino, et al. \(2014\)](#), [Iuorio, et al. \(2014\)](#), [Khalifa, et al. \(2020\)](#) and [Wang and
130 Hutchinson \(2020\)](#).

131 **2.2 Risk management in construction industry**

132 Intending to apply risk management in LSF construction system, a brief literature review of
133 the risk management in construction industry is provided here. Risk Management in
134 construction projects has been applied since 1990 to identify, analyse and respond to risk
135 factors in a project and maximise the results of positive events and minimise the consequences
136 of negative events effected project objectives ([Renuka, et al., 2014](#), [Wang, et al., 2004](#)).

137 Construction projects are among the most important projects that are being implemented in any
138 country. These projects are of great importance due to the consumption of many resources, the
139 existence of different stakeholders and the impact on other sectors. One of the first application
140 of risk identification and classification can be seen in the research conducted by [Mustafa and
141 Al-Bahar \(1991\)](#). They categorised project risks based on project objectives into six groups of
142 hazards including uncontrollable natural forces, physical, financial, political, design and job
143 related ones. [Zou, et al. \(2007\)](#) and [Zou and Zhang \(2014\)](#) identified and classified risks of
144 construction projects in China and Australia based on Project Life Cycle (PLC) defined through
145 feasibility, design and construction phases. Other researchers also used PLC and project
146 objectives for risk classification ([Mehdizadeh, et al., 2012](#), [Zeynalian, et al., 2013](#)). Also [Goh,
147 et al. \(2013\)](#) used PLC to categorise a university project's risks in Malaysia, and calculated
148 likelihood, impact and risk level for each risk. [Oduyemi, et al. \(2016\)](#) suggested that by
149 detection of risk factors in design stage, improvement in project goals was acquired and hence
150 risk classification based in PLC can be useful.

151 Comparing risk importance in each class is one of the main objectives of risk classification. To
152 compare risks in each class, statistical methods is very common. For example, [Wu, et al. \(2019\)](#)
153 classified risks in off-site constructions into four categories include general, design-related,
154 construction-related, and people and organisation-related and compared expert's opinion with
155 statistical tests. Delphi technique, brainstorming, expert judgment and interview are the most

156 common tools for risk identification and classification. Although risk identification and
157 classification as a key part of risk management need no complex calculations, few researches
158 have exclusively done this part of risk management and most of the papers report previous
159 risks in their model (Renuka, et al., 2014). Some researchers such as Dey (2012) and Franklin,
160 et al. (2020) simultaneously used literature review and risk identification techniques.

161 Several techniques such as probability-impact matrix, Monte Carlo simulations, likelihood
162 occurrence of risk, Fuzzy Set Theory (FST) and FMEA could be used for risk assessment or
163 evaluation (Renuka, et al., 2014). The significance of the risks is usually determined based on
164 probability of risk occurrence and the risks impact or degree of loss (Wu, et al., 2019) or
165 relation of some risk factors (Forcael, et al., 2018, Wang, et al., 2018).

166 In a general case, these methods require probability and effect of the risks in the project
167 objective based on expert's opinions. In projects, we deal with the risks associated with the
168 project objectives. Therefore, a clear prerequisite for identifying project risks is a clear
169 understanding of the project objectives (Liu, et al., 2016). For transferring expert judgment to
170 numeric information for risk evaluation, we can use FST or fuzzy reasoning Membership
171 Function (MF). Various publications since 1996 until now have shown the performance of this
172 technique in risk assessment in construction projects (Chan, et al., 2009). Fuzzy rules have also
173 been used in risk management in construction project (Asadi, et al., 2018).

174 The next step in risk management is risk responding. Wu, et al. (2018) introduced five main
175 categories for risk response methods including zone based, Work Breakdown Structure (WBS)
176 based, trade-off based, optimisation based and other methods. The first three groups have fewer
177 complex calculations and can be easily used in construction projects but it could not be known
178 whether the risk response actions are the optimal solution in these methods. Seyedhoseini, et
179 al. (2009) and Abdelgawad and Fayek (2010) are the instances of the works in these groups
180 respectively. On the other hand, the researches in fourth and fifth groups such as Wu, et al.
181 (2018) employed optimisation problems and heuristic or meta heuristic algorithm to reach an
182 optimal answer among risk responses. These methods not only are defined by complex
183 problem-solving algorithms but also need precise information about project objective such as
184 cost, time and quality. It is a common way to firstly detect different risk response strategies
185 that optimise the performance of construction projects and then relevant solutions to the best
186 strategy are compared. Choudhry and Iqbal (2013) proposed some response strategies entailing
187 avoidance, transferring, reduction, sharing and retaining and ranked them based on experts'
188 judgment.

189 FMEA techniques investigate adverse effect of risks of the entire system during the failure of
190 the system. These techniques have been applied to the US aerospace industry from the 1960s
191 for safety and reliability analysis (Bowles and Peláez, 1995). Then, they have been frequently
192 used as a tool to evaluate the risk in various industries such as automotive health-related
193 problems, marine fields, nuclear processes, electronic and asset management (Abrahamsen, et
194 al., 2016, Baghery, et al., 2018, Braaksma, et al., 2013, Kang, et al., 2017, Yeh and Chen,
195 2014). In addition, it has widely been applied to construction management problems (Kim and
196 Kim, 2012). Abdelgawad and Fayek (2010) applied FMEA for risk assessment of construction
197 projects and used fuzzy logic to improve its capability with uncertain information of experts'
198 judgments similar to Cheng and Lu (2015). Considering some modifications in the FMEA
199 formulation, Seifi Azad Mard, et al. (2017) introduced a novel approach for risk evaluation of
200 occupational outcomes. There are several other researches about implementation of FMEA in
201 the construction industry that can be found in Chin, et al. (2009), Gargama and Chaturvedi
202 (2011), Liu, et al. (2019), Ma and Wu (2019).

203 In contrast to focusing in a specific part of risk management, some researchers such as Wang,
204 et al. (2004), Abdelgawad and Fayek (2010), Dey (2010), Dey (2012) and Ahmadi, et al. (2017)
205 proposed a framework for risk management in construction projects and consider the entire
206 aspects of risk management in their methods. The risk responding procedure in these
207 frameworks is related to risk assessment parameters and can be easily applied to all types of
208 construction project. For example, Ahmadi, et al. (2017) proposed a framework for a roadway
209 project consisting of risk evaluation and response based on FST and risks were evaluated based
210 on probability, severity of consequence on project objectives and control ability of the project
211 team.

212 In some researches, the risk management term is incompletely utilised for the above process in
213 construction project (see for example Goh, et al. (2013)). Using risk management term, we
214 should perform several accurate steps based on PLC from identifying to responding and
215 controlling of project risks so it is better to say risk identification and analysing for above
216 research. Ashley, et al. (2006) and Iqbal, et al. (2015) have completely defined risk
217 management in construction projects and described the matters should be considered in
218 applying risk management, but in more cases risk identification, evaluation and responding
219 have been tangibly seized by researchers. Also, Choudhry and Iqbal (2013) described risk
220 management barriers in construction project and compared different tools in risk management
221 based on expert judgment and showed that there was lack of systematic risk management in
222 construction projects especially in developing countries.

223 As we want to apply risk management in special type of construction project (LSF system),
224 some similar works in other types of projects have been hitherto done. Cause of delays in
225 construction projects (Banobi and Jung, 2019), investigation of risks magnitude in tunnel and
226 railway projects by three simple risk indices including probability, severity and frequency
227 (Forcael, et al., 2018), risk analysing in modular construction (Li, et al., 2013) and
228 determination of risk importance in industrialized building system (IBS) projects (Bari, et al.,
229 2012) are some instance of risk identification and assessment in special type of projects.

230 **2.3 The aims and innovations of the study**

231 Previous researches on the risk management in the construction industry mainly focused on the
232 implementation of the risk management in the LSF system and a wide knowledge gap was
233 identified. This paper provides a comprehensive framework for risk management of the LSF
234 system entailing risk identification, risk evaluation and proposing appropriate strategies to
235 respond the risks during design, construction and operation steps. Moreover, due to the limited
236 expansion of the LSF system in developing countries, this research would be of high
237 importance for application of this system in these regions. The main contributions of the paper
238 can be summarised as follows:

- 239 • Identifying key risks of LSF structures;
- 240 • Classifying the identified risks under PLC and other relevant subjects;
- 241 • Evaluating the identified risks through a novel Fuzzy FMEA approach;
- 242 • Proposing appropriate response strategies for the identified risks;
- 243 • Demonstration of the proposed methodology in a real-world case study;

244 The FMEA method as a risk assessment technique can identify and evaluate potential risks and
245 their causes and effects. Risk management of construction projects has many ambiguities and
246 unknowns (Chin, et al., 2008). These uncertainties sometimes result in either better or worse
247 outcomes (Kumru and Kumru, 2013). These uncertainties and associated risks can lead to some
248 complexities between the project components and even unstable conditions that can change the
249 project outcome due to some external reasons such as governmental laws (Chin, et al., 2008).
250 Fuzzy theory has shown to be a useful tool to deal with these types of uncertainties in the
251 decision making.

252 Fuzzy theory is a computing method using "degrees of truth" rather than the traditional "true
253 or false" (1 or 0) Boolean logic that underpins modern computers (Meng Tay and Peng Lim,
254 2006). The concept of fuzzy sets was introduced by Zadeh in 1960s for the first time (Jong, et
255 al., 2013). In this approach, a fuzzy set described the concepts of a fuzzy number by using a

256 degree of membership of its elements in a universe of discourse (Sang, et al., 2018). Fuzzy
257 numbers defined in the interval $[0,1]$ provide semantics for terms in a linguistic term set, which
258 are represented by MF that can be classified by types of functions. Fuzzy set theory is also used
259 in a fuzzy inference system (FIS) to generate a model between inputs (features in the case of
260 fuzzy classification) and targets (classes in the case of fuzzy classification). Due to the use of
261 FIS, such transition may need a set of fuzzy rules in which gathering a complete one is difficult
262 (Jee, et al., 2015, Kerk, et al., 2021). Previous researches have indicated all of the above
263 concepts could adopt to the risk analysis due to the capability of fuzzy concept for modelling
264 of uncertainty.

265 Combining the FMEA method with fuzzy theory provides a more efficient tool than the original
266 FMEA method at the presence of vague concepts, insufficient information and uncertainty.
267 Fuzzy logic could reduce the drawback in assessing and prioritizing failures of traditional
268 FMEA (Chanamool and Naenna, 2016). Hence, this paper provides a novel Fuzzy FMEA
269 technique for risk assessment in construction projects.

270 **3 Methodology**

271 The proposed framework for dealing with risk management in the LSF system is illustrated in
272 Figure 1. The framework comprises three main phases including 1) risk identification and
273 classification; 2) risk assessment and 3) risk response. The first phase identifies the related
274 hazards and potential risks to the LSF system through reviewing several LSF projects, relevant
275 literature and interviewing relevant experts in these projects. The identified risks are also
276 classified based on the life cycle, objectives and stakeholders of the projects.

277 The second phase entails quantifying the level of risk for each hazard identified in the LSF
278 system by calculating risk parameters based on a Fuzzy FMEA approach. FMEA combines
279 technology and experts' experiences for identifying and planning for the removal of
280 foreseeable failure modes of a product or process. It is used in various phases of the product
281 life cycle in the manufacturing industries and is now becoming increasingly common in the
282 service industry (Chin, et al., 2008). In order to assess the risk level of a component or process,
283 traditional FMEAs use the risk priority number (RPN). The RPN is determined by multiplying
284 three factors: the probability/occurrence of failure, the seriousness of failure and the probability
285 that a failure is not detected (Balaraju, et al., 2019, Chanamool and Naenna, 2016, Kumru and
286 Kumru, 2013). Precision should not be imposed if the data is unreliable and scarce when
287 conducting FMEA for safety assessment purposes. Hence, it would be unrealistic to ask an
288 analyst or expert for scoring from 1 to 10 (as in the RPN method), for the various factors being

289 examined. Although this simplifies the calculation, the probability is converted to another score
290 system and the multiplication of factors is believed to cause problems. There are different
291 relationships as either linear or nonlinear between probabilities and factors (Balaraju, et al.,
292 2019).

293 A Fuzzy FMEA approach was utilized in this paper to overcome the weaknesses associated
294 with the traditional RPN ranking system. As a proper guideline, the proposed method has been
295 inspired by the Figure 1 in Balaraju, et al. (2019). To this end, risks are then prioritised and
296 ranked based on a multi-criteria decision analysis and fuzzy reasoning method. Appropriate
297 strategies for risk response are then considered as solutions to mitigate the impact of each risk
298 in phase three. A new objective-based index is defined based on the main criteria of the
299 construction projects and used in this phase to prioritise the analysing strategies in this phase.
300 The methodology is demonstrated through a real-world case study in Iran as a developing
301 country. The steps taken at each phase is described below in further details.

302

303 Figure 1. The methodology flowchart

304

305 **3.1 Risk identification and classification**

306 This step comprises two parts: (1) risk identification and (2) risk classification. Potential
307 hazards and related risk events are first identified through various resources including interview
308 with individuals involved in LSF construction projects and literature review of previous works
309 (Luo, 2015). The interview is worthwhile because it can reveal new potential risks that have
310 yet to be identified or analysed by researchers. The individuals participating in the interview
311 could be from a wide range of expertise and different roles such as designers, workers, owners,
312 engineers, residents and employers.

313 Risk classification is mainly used to compare the significance of the risk events in the classes
314 sharing the same characteristics. Hence, identified risks in LSF system are classified here under
315 three major categories with respect to: (1) PLC i.e. design, construction and operation; (2) main
316 project objectives including cost, time, quality, safety and environmental sustainability; and (3)
317 project stakeholders including clients, designers, contractors, government bodies and external
318 issues (Zou and Zhang, 2014, Zou, et al., 2007). Expert judgment is used here to identify the
319 class of each identified risk through a questionnaire based on the greatest number of votes
320 received for each class.

321 **3.2 Risk assessment**

322 This phase entails two main steps for risk analysis and prioritisation of the identified risks. The
 323 FMEA technique and the FST method are adopted here to analyse qualitative expert's
 324 judgements and convert them to risk factors (Ahmadi, et al. (2017)). This technique quantifies
 325 each risk with three main components including Control Number (CN) or the control ability of
 326 the project team to handling the risk, Probability of occurrence (P) and Consequence (C) of
 327 occurring corresponding hazard (risk magnitude) on the project criteria or objectives. In fact,
 328 the risk magnitude calculates severity of consequence for five project's subcomponents
 329 entailing cost (C_c), quality (C_q), time (C_t), safety (C_s) and environment (C_e). Hence, Risk
 330 Criticality Number (RCN) in the FMEA method is defined as (hereafter fuzzy numbers are
 331 shown with $\hat{}$ and crisp (real) values are simple):

$$332 \quad RCN = \hat{P} \times \hat{C} \times CN \quad (1)$$

333 Thus, this model not only considers probability and impact of the risks but also involves the
 334 ability to control the risk and provides a comprehensive risk index for evaluation process. It
 335 should be noted that the CN index, indicating the ability of identifying or controlling the risk
 336 is performed in reverse; in other words, the higher risk control, the less severity it would have
 337 on the effect of risk and so smaller CV . Cost, quality and time are three common objectives in
 338 the construction industry but safety and environmental factors are added here due to their
 339 importance within the sustainability framework of development. Hence, the overall risk
 340 consequence (\hat{C}) is calculated by using a weighted combination (i.e., related weights) of the
 341 above objectives:

$$342 \quad \hat{C} = \hat{C}_q \times W_q + \hat{C}_t \times W_t + \hat{C}_c \times W_c + \hat{C}_s \times W_s + \hat{C}_e \times W_e \quad (2)$$

345 To calculate the fuzzy number components of the RCN with FST and FMEA methods, the
 346 following steps are needed which are described in more detail.

347 **Step 1: Definition of linguistic terms**

348 The same approach as Ahmadi, et al. (2017) is utilised for definition of qualitative factors or
 349 linguistic terms here. Linguistic terms for pairwise comparison of the criteria's weight are
 350 strongly more, more, equal, less and strongly less with triangular MF and for
 351 $\hat{C}_q, \hat{C}_t, \hat{C}_c, \hat{C}_s, \hat{C}_e, CN$ and \hat{P} are very low, low, equal, high and very high with trapezoidal MF.

352 **Step 2: Determination of criteria's relative weights**

353 Risk consequence related to five criteria including cost, quality, time, safety and environmental
354 issues and the relative weight of these criteria (W_c, W_q, W_t, W_s and W_e) are obtained with ten
355 pairwise qualitative comparison of criteria relative preferences (i.e., cost vs time, cost vs quality,
356 cost vs safety, cost vs environmental issues, time vs quality, time vs safety, time vs
357 environmental issues, quality vs safety, quality vs environmental issues, safety vs
358 environmental issues). The final criteria relative weights are obtained by implementation of
359 fuzzy AHP technique which enables a pairwise comparison between these criteria by using
360 linguistic terms. Finally, relative weight of each criterion will be used to acquire a single
361 severity of consequence (\hat{C}) for each risk event based on equation (2).

362 **Step 3: Applying relative weight of experts**

363 Determination of respondents' score or weight usually is a part of risk analysis. To this end,
364 respondents were ranked and weighted here based on their professional experience (from less
365 than 5 years to over 30 years), job position (from simple worker to employer), and educational
366 level (from elementary education to PhD). For each item, respondents could earn 1 to 5 score.
367 So, for each person, final score ranges between 3 to 15. The relative weight of each expert is
368 calculated by dividing the absolute weight of the expert by sum of absolute weights of all
369 experts.

370 The expert chosen linguistic terms of $\hat{C}_q, \hat{C}_t, \hat{C}_c, \hat{C}_s, \hat{C}_e, CN, \hat{P}$ and pairwise comparison of
371 criteria (through questionnaire survey) are multiplied into the expert relative weight then by
372 combining the expert judgments with α – cut method into a single fuzzy number, the final MF
373 of each component is obtained.

374 **Step 4: Prioritising the risk events**

375 To calculate $R\hat{C}N$, a single fuzzy number for severity of consequence (\hat{C}) is calculated from
376 equation 2 using α – cut method in the first step. Then, a single fuzzy number for probability
377 of occurrence (\hat{P}) and control ability (CN) is also obtained by incorporating the fuzzy numbers
378 of experts' judgements. The fuzzy number of $R\hat{C}N$ is calculated by fuzzy multiplying of these
379 three fuzzy numbers using α – cut method through equation (1). The risks are ranked in
380 accordance with their crisp values of $R\hat{C}N$ in doing so important risks have greater RCN .

381 **3.3 Risk responding and validation of responses**

382 Following consecutive steps lead to suitable responses for a risk event considering the risk
383 response strategy. Also, a case-based validation scheme for evaluating the reliability and
384 accuracy of the responses is suggested.

385 **Step 1: Identifying possible risk solutions**

386 Risk solutions, as open-ended form questionnaire the same as [Dosumu and Aigbavboa \(2018\)](#),
387 are questioned from experts for each risk. Hence a list of risk solutions is provided for each
388 one.

389 **Step 2: Calculating the risk response strategy**

390 [Abdelgawad and Fayek \(2010\)](#) proposed risk response strategy selection based on *RCN* value
391 and [Ahmadi, et al. \(2017\)](#) modified this method considering *RF* and *CN*. The proposed method
392 here as shown in Figure 2 considers crisp values of *RCN*, *CN* and *RF* in which the risk action
393 is classified under four ranges: **Range 1**: risk acceptance; **Range 2**: risk transference; **Range**
394 **3**: risk mitigation / risk avoidance; **Range 4**: risk mitigation / risk avoidance / risk transference.
395 The ranges are specified based on three crisp limits i.e., L_1 , L_2 and L_3 which are indicator of *RF*,
396 *CN* and *RCN* decision limits. To this end, the fuzzy number *RF* is calculated with α -cut
397 method as:

$$RF = P \times C \quad (3)$$

398
399
400 By defuzzification of *RF*, two states i.e., *RCN*-based state and *CN*-based state are generated
401 in the response strategy chart shown in Figure 2.

402 If the *RF* is lower than L_1 , the crisp value of *RCN* (without consideration of *CN*) determines
403 the response strategy hence if *RCN* would be greater than L_3 , the risk assigns and the
404 transference strategy is suggested else the risk can be accepted. In other words, risk transference
405 is used for range 2 in our proposed method instead of acceptance in comparison to [Ahmadi, et](#)
406 [al. \(2017\)](#) and it means that the risks with low control ability (high value of *CN*) should be
407 transferred ([Ashley, et al., 2006](#)). Note that the risks located in range 2 have small value of *RF*
408 and high value of *RCN* due to high value of *CN*. For the risks that have *RF* value greater than
409 L_1 or located in *CN*-based state, the risks are assigned to each range based on *CN* and the *RCN*
410 is not considered.

411 For justification about other ranges reader is referred to [Abdelgawad and Fayek \(2010\)](#). We
412 suggested 30% of maximum value of MF for L_1 then the average of *CN* for the risks with *RF*
413 values greater than L_1 is considered as L_2 . In other words, the predefined MF of *P* and *C* are
414 within the range of 0 to 10 in this paper so the *RF* value would be within 0 and 100. With this
415 aim, L_1 is equivalent to 30 and the average of *CNs* for the risks that have *RF* value greater than
416 30 are considered as L_2 . The value of L_3 is approximated based on risks located near the point

417 (L_1, L_2) providing that the values of RCN are alleviated toward centre (for details see Figure 2
418 in [Ahmadi, et al. \(2017\)](#)).

419

420

Figure 2. selection the risk response strategy based on RCN , CN and RF

421

422 **Step 3: Validation of risk responses**

423 To establish the reliability of the survey, [Choudhry and Iqbal \(2013\)](#), [Oduyemi, et al. \(2016\)](#)
424 and [Forcael, et al. \(2018\)](#) used statistical methods such as correlation between results and
425 hypothesis test and acceptable range for the results is mathematically calculated in this manner.

426 In a different manner, [Wang, et al. \(2004\)](#) and [Dey \(2012\)](#) validated their methods based on
427 expert judgment about research findings. If we want to use statistical or mathematical methods
428 in the results validation, the risk evaluation should be also done based on them. Because the
429 risk evaluation is performed based on expert judgment, validation of results once again by
430 experts would not be a scientific manner and will be intensively influenced by respondent
431 responses. Hence, we avoid of using of these methods for validation of responses.

432 In this paper, the Scope Expected Deviation (SED) index proposed by [Seyedhoseini, et al.](#)
433 [\(2009\)](#) as shown in equation (4) is used in order to validate the responses. The SED index will
434 be used in the case that we have only one project and all the scopes are defined and information
435 about time, quality and cost of the project are needed. For this purpose, the procedure should
436 be performed in a pilot LSF project the same as [Asadi, et al. \(2018\)](#).

$$437 \quad SED = W_q \times \frac{Q_0 - Q}{Q_0} + W_t \times \frac{T - T_0}{T_0} + W_c \times \frac{C - C_0}{C_0} \quad (4)$$

438 In the above formula, the zero index in quality, time and cost (Q_0, T_0, C_0) means the aim of the
439 project while the ultimate state of quality, time and cost are shown with Q, T and C respectively.

440 [Seyedhoseini, et al. \(2009\)](#) suggested drawing of WBS, Quality Breakdown Structure (QBS)
441 and Cost Breakdown Structure (CBS) and determination of final time, quality (equal to 1) and
442 cost based on these charts. The final value of cost, time and quality (or specification of project
443 outputs) have been broken down hierarchically to lower levels based on expert judgment or
444 Delphi method. To calculate the project quality, reaching to project specifications is measured
445 and the final quality is obtained by summation of independent items' quality and production of
446 dependent ones.

447 After calculation of the effect on each risk action on these three criteria, the SED index is
448 obtained. If the suggested solutions generate negative value of RCN , the results will be

449 validated and vice versa. For more description the reader is referred to [Seyedhoseini, et al.](#)
450 [\(2009\)](#).

451 It should be noted that it is possible to include safety and environmental issues in the *SED* index
452 but there is not a simple and practical manner for determination of these factors after and before
453 the risk solutions. To this end, for each risk the *SED* is calculated for all suggestive solutions
454 that coordinated to risk response strategy. If minimum value of *SED* among suggestive
455 solutions is negative for all the risks, the validity of the results is confirmed. Should we offer a
456 proper justification or recommendation for solutions with positive *SED*, the results can still be
457 accepted otherwise some necessity actions should be suggested for them.

458 As shown in Figure 1, the questionnaire is used for gathering the expert's views. The structure
459 of the questionnaires given to each respondent is shown in Table 1. Risk consequence is related
460 in this research to five criteria including cost, quality, time, safety and environmental issues
461 and the first questionnaire (first row of Table 1) is related to preference of cost, quality, time,
462 safety and environmental issues (W_c, W_q, W_t, W_s and W_e). So, this questionnaire consists of ten
463 questions about pairwise comparison of criteria's preferences and finally provides a relative
464 weight for each criterion. The questionnaire is also comprised nine other sections (second to
465 tenth row of Table 1) to identify three main components such as C, CN, \hat{P} and five
466 subcomponents including $\hat{C}_q, \hat{C}_t, \hat{C}_c, \hat{C}_s$ and \hat{C}_e . If N risks were identified through risk
467 identification process, $N+1$ sets of questionnaires are given to each respondent. The first one
468 in this set has only Questionnaire No. 1 but other sets include the Questionnaires No. 2, 3, ..., 9
469 and 10 for each risk. Additionally, risk class and risk solution, as open-ended form (ninth and
470 tenth rows of Table 1) the same as [Dosumu and Aigbavboa \(2018\)](#), are questioned from experts.

471

472 Table 1. The structure of the questionnaire

473

474

475 **4 Results and discussion**

476 LSF buildings in the design, construction and operation phase is applied as a case study in this
477 research in two main cities of Iran, as a developing country i.e., Tehran and Mashhad. The data
478 for identifying the key risks was collected through a 3-months face to face interview with
479 engineers, designers, residents, employers and other related persons to designing, construction
480 and operation phase of LSF system. Overall, through information collected from interviews
481 and a comprehensive reviewing of literature, 29 risks ($N=29$) are extracted. In the next step, 30

482 questionnaires as defined in Table 1, was sent by hand or through an email to ask people's
483 opinion and among them, 132 persons (representing about 60 percent of the sample frame)
484 filled and returned the questionnaires. These 132 interviewees earned 58 % of total scores of
485 respondents' weight considering professional experience, job position and educational level.

486

487 **4.1 Identified risks**

488 Table 2 lists the identified risks and other characteristics of each one (described in the following
489 sections). Among them, DAC (Barnard, 2011, Celik and Kamali, 2018), RWF (Darcy and
490 Mahendran, 2008, Yu, 2016), DEB (Khalifa, et al., 2020) and IG (Zeynalian, et al., 2013) were
491 extracted from literatures. Note that we merged similar risk suggested by interviewees as one
492 risk, for example different problems related to façade of LSF buildings were stated by some
493 people and we represented all these issues as DFI risk.

494

495 Table 2. Calculating the model's components for identified risk in the ascending order of *RCN*

496

497 **4.2 Classification of identified risks**

498 The second column of Table 2 shows the classification of each risk based on PLC, project
499 objective and stakeholders respectively. For better illustration, association of risks in PLC with
500 stakeholders and objective shown in Figure 3 with two fishbone diagrams. It is concluded that
501 the share of risks in design, construction and operation steps are 21%, 31% and 48%,
502 respectively. This finding is partly in line with Zou, et al. (2007), Bari, et al. (2012),
503 Mehdizadeh, et al. (2012), Goh, et al. (2013) and Forcael, et al. (2018), which showed more
504 risks are related to construction than designing in the construction industry. But technically,
505 they did not consider operation because they thought operation risks have root in designing or
506 construction. On the other hand, albeit Zou and Zhang (2014) had considered operation phase
507 in their model, they identified more risks in construction than other phases in high-rise building
508 projects.

509

510 Figure 3. The fishbone diagram in accordance to stake-holders vs PLC (first panel) and objectives vs PLC

511

(second panel)

512

513 Although we only located each risk in one class based on experts' opinion, the classification
514 results were mostly the same with other research. For example, locating of LPS in safety
515 category (Zou, et al., 2007), LSC in designing (Mehdizadeh, et al., 2012), IW in construction

516 or construction (Zou and Zhang, 2014) , VMP in external issues (Forcael, et al., 2018), VMP
517 and FIM in safety (Lu, et al., 2018) are some instances. Some inconsistencies have also been
518 shown in classification in contrast to other researches. Forcael, et al. (2018) assigned hazardous
519 conditions to contractors but FIM is located in external issues class based on our experts.
520 Several reasons such as not carrying out fire preventing actions, using of arsonist materials in
521 building construction and lack of firefighting equipment in workshop during construction phase
522 can be expected on the occurrence of ignition in construction projects. In contrast to these
523 contractor-related factors, some external reasons like wind, thunderbolt and electrocution could
524 be mentioned for firing's cause and our experts classified FIM into second group.
525 The majority of contractor's risks are related to construction (Zou and Zhang, 2014) but our
526 experts ascribed these to both construction and operation phases. It means that if the contractor
527 incorrectly performs the construction process, this might cause defects in operation phase. For
528 example, DSW or hearing some annoying noises from LSF walls could be caused due to wrong
529 installation of studs in construction phase. But it will be usually discovered in thermal
530 expansion and contraction conditions (i.e., studs' length may be reduced or augmented because
531 of expansion and contraction) after installing gypsum board and painting.
532 Liu, et al. (2016) stated that lack of labour's experience effects on project quality, but our
533 finding showed that the UEGC risk impacts on the cost of project. This risk derived from
534 labour's mistake causes rework in project, so excess time and cost (time or cost overrun) are
535 needed and the effect of cost is greater than time based on our experts.

536 **4.3 Determination of the risk response strategy**

537 The risk response range is illustrated in last column of Table 1 based on the *RCN*, *RF* and *CN*
538 described in the third, fourth and fifth columns of Table 2. To calculate the limits based on
539 considered MF, L_1 is equivalent to 30 and L_2 is obtained equal to 3.59 (average of *CN*s for the
540 risks that have *RF* value greater than 30). Based on the risks located near the point (30, 3.59)
541 the value of L_3 is approximated to 149. The risks in each range and their classification in terms
542 of PLC (design with triangular, construction with circle and operation with square shape) are
543 shown in Figure 4.

544

545 Figure 4. Assignment of risk response range in term of design (triangular), construction (circle) and operation
546 (square) phase

547

548 We can conclude that only 15% of the risks can be accepted based on the proposed method and
549 the solutions for other risks should be defined considering suitable response strategy. Among

550 non-accepted risks, only 3 risks including LDBH, WCP and DEB are located in range 2 in
551 which there are low probability of occurrence, risk impact and control ability.
552 Dealing with these risks, we have not several solutions for controlling them. Our model
553 suggested transferring strategy instead of acceptance for these risks. For instance, should we
554 want to construct a high rise building with LSF system (LDBH), [Ahmadi, et al. \(2017\)](#)'s model
555 accepts this risk and has any solution. Combination of shear wall with LSF system is a good
556 and feasible choice and may be considered as a transfer strategy. Although [Franklin, et al.
557 \(2020\)](#) stated that overdesigning could occur in combination of other structure systems with
558 LSF, using of the LSF system can reduce danger of earthquake for some seismic regions.
559 Construction of LSF combined with shear wall for a 7 story school is shown in left panel of
560 Figure 5. [Yu \(2016\)](#) suggested panelization or assembling the components of the LSF in a
561 controlled manufacturing environment, and this system as shown in right panel of Figure 5 fits
562 very well in high-rise buildings.

563

564 Figure 5. Left panel: Combination of LSF system with shear wall in a 7-story school. Right panel: panelization
565 in LSF buildings ([Yu, 2016](#))

566

567 If high-rise buildings were executed with LSF system, the construction industry in developing
568 countries would enable to reach a rapid expansion and as mentioned by [Fallah \(2005\)](#) and [Celik
569 and Kamali \(2018\)](#) a recyclable construction system with a lot of positive environmental
570 impacts regarding its sustainability, refurbishment, recyclables and reusability issues. For a
571 specific detail, [Celik and Kamali \(2018\)](#) mentioned minimum rework, waste and preparation
572 work in running piping and electrical wiring in LSF system. Hence, this risk has a constructive
573 impact on the environmental sustainability and this is the main reason of categorizing this risk
574 and FUS in environmental sustainability group by our experts. In other words, if people's
575 perception and feeling of unreliability of LSF structure is reduced, an environmentally friendly
576 system with many environmental benefits will expand.

577 **4.4 Discussion on the risks' magnitude**

578 After applying the model on the data obtained from the interviews and questionnaires,
579 computational indexes for each risk were calculated. Risks are sorted by *RCN* in third column
580 of Table 2. The objectives' weights were assigned equal to $W_q = 0.14$, $W_c = 0.4$, $W_t = 0.22$,
581 $W_s = 0.13$ and $W_e = 0.11$ by experts' judgment and fuzzy AHP technique from pairwise
582 comparisons of the criteria (results are not shown) and these weights are the same for all the

583 risks. As an example, the single fuzzy numbers related to the five criteria ($\hat{C}_t, \hat{C}_s, \hat{C}_q, \hat{C}_c$ and
584 \hat{C}_e) for consequence of the risk event of IWO is shown in Figure 6 respectively.

585

586 Figure 6. Fuzzy numbers for consequence of the risk event of IWO related to $\hat{C}_t, \hat{C}_s, \hat{C}_q, \hat{C}_c$ and \hat{C}_e
587 respectively

588

589 Having incorporated these fuzzy numbers ($\hat{C}_t, \hat{C}_s, \hat{C}_q, \hat{C}_c$ and \hat{C}_e), the single fuzzy number C
590 is then obtained for each risk event by equation (2). The combination of these five criteria using
591 relative weights and the α -cut method yields C shown in the first panel of Figure 7 for IWO.
592 This fuzzy number $R\hat{C}N$ shown in the fourth panel of Figure 7 is resulted by the fuzzy
593 multiplication of C, CN and P based on equation (1). These fuzzy values (CN and P) are
594 also calculated by combining the experts' judgement for this risk event shown in second and
595 third panels of Figures 7. Also, the fuzzy number of RF based on equation (3) is shown in the
596 last panel of Figure 7.

597

598 Figure 7. Fuzzy numbers for $\hat{C}, CN, \hat{P}, R\hat{C}N$ and RF for IWO

599

600 To check the reliability of risk's ranking, a comparative analysis on the risk importance, risk
601 response strategy and risk solutions is performed with other works discussed the same risk as
602 us. Since the question on the solution to the risks was open-ended i.e., the respondents were
603 required to mention and explain their opinions, for the sake of brevity all the solution's results
604 were not reported and principal items have been briefly discussed. It is worth mentioning that
605 some unimportant risks in this research like LSC, DAC, RWF and NGP are region-sensitive
606 and if a similar research is done in a different country, the risk's rank may be changed. For
607 example, the danger of corrosion (DAC) in most of the provinces in Iran is low or designer
608 usually consider lowest possible wind speed in construction design in Iran. So, this could be
609 the possible reason why the respondents did not consider DAC and RWF as highly ranked
610 risks.

611 **DFI:** The DFI relates to dry façade in LSF buildings is shown in Figure 8. Two unbearable
612 problems relating to dry facades were extracted from expert's suggestions. The first which has
613 low importance is occurred in striking some heavy things like stone to dry facades (right panel

614 in figure 8) but the second risk that also has high probability in Zeynalian, et al. (2013) means
615 that the dry façade destructs during the time because of bad construction or insulation (left
616 panel in Figure 8) because of penetration of rain water into the building facades.

617

618 Figure 8. Dry facades problems in LSF system: right panel: striking some heavy things to dry facades. Left
619 panel: bad performance of construction or insulation

620

621 A solution for that is to use movable roof for the purpose of preventing against raining. Of
622 course this is too expensive, and using of insulated material such as sarking materials (Barnard,
623 2011) can be more feasible. Other remedies suggested by Soares, et al. (2017) are using two
624 membrane layers and using external wind-tightness layer for avoiding moisture. Yu (2016)
625 opined that failure in workmanship of facades caused this risk. They proposed offsite
626 construction and prefabrication as a transferring strategy. Also, a feasible and optimized
627 solution called white cement facades, discussed in validation section, was suggested by one
628 expert.

629 **IWO:** Among all risks related to LSF system identified in the current research, IWO is the one
630 with higher priority. Most of individuals interviewed have declared that the most important
631 problem of dry-wall systems is the impossibility of installing heavy objects on the walls. As
632 shown in Figure 9, there are many solutions to this issue including use ribbed plastic anchor,
633 self-drilling anchor, toggle bolts, molly bolts and marking the place of studs on walls or finding
634 the studs placement. In addition, walls with double boards have more capacity for installing
635 heavier objects (Veljkovic and Johansson, 2006). LSK (2007) has also suggested some useful
636 guidance about screw, pin, clinch and rivet in LSF walls.

637

638 Figure 9. a: ribbed plastic anchor, b: self-drilling anchor, c: toggle bolts, d: molly bolts and e: marking the place
639 of studs

640

641 Despite these solutions, designers, engineers and clients have a negative attitude to dry-wall
642 system among respondents specially because of comparing to masonry systems; in other words,
643 there is a relationship between this risk and FUS; however, possibly people's awareness to dry-
644 wall system can be very effective in their belief.

645 **4.5 Comparing average of RCN for each class**

646 Figure 10 draws a comparison between the risks of the PLC, project objective, project
647 stakeholders and risk response range classes based on average acquired *RCN*. Results show
648 that construction, cost, contractor and range 4 have higher importance among other classes.

649

650 Figure 10. The average *RCN* of the risks in the PLC, project objective, project stakeholders and risk response
651 range classes

652

653 Based on the ranges of the PLC risks, those belonging the higher *RCN* i.e. range 4 seems
654 rational. On the other hand, we can conclude from Figure 10 that the importance of construction
655 and operation risks have higher than that in design risks. **It should be noted that literature has**
656 **different findings for the level of importance of the relevant risks that can be either in line or**
657 **against the finding in this study. For example, Wang, et al. (2018) showed the most significant**
658 **risks based on Pareto principle are those related to the operation phase while Mehdizadeh, et**
659 **al. (2012) showed that risks associated with the construction phase are more important than the**
660 **design risks in construction projects. Contradictory findings have also been reported for**
661 **prefabricated buildings in which the design risks have the greatest impact on the final**
662 **performance of the system (Yuan, et al., 2020). These various findings can be due to the several**
663 **reasons such as construction methods, the risk analysis model entailing meta network analysis,**
664 **grounded theory, analytic network process (ANP), the linear weighted sum method and**
665 **structured self-intersection matrix that might have been effective in these conclusions. Some**
666 **other related justifications and discussions can be found in Xiahou, et al. (2018) and Lu, et al.**
667 **(2018).**

668 The cost and quality are the most important objectives in this model and time has the minimum
669 average of *RCN*. But Zou and Zhang (2014) consider cost and time as important risk's group.
670 Having higher speed of construction procedure in LSF buildings than conventional buildings
671 can justify this contradiction so the time-related risks have lower important. Zeynalian, et al.
672 (2013) stated that fabrication and installation of LSF components in the factory could enhance
673 the control ability of time and quality related risks.

674 **4.6 Effect of *CN* in the risk evaluation**

675 Only do conventional methods consider probability and impact of the risk in determination of
676 risk magnitude while control ability is also considered in determination of risks' rank here.
677 Intending to discard *CN* in risk evaluation, we can evaluate risks based on *RF*. The risk rank
678 based on *RCN*, *RF* and absolute difference between them are shown in Figure 11.

679

Figure 11. The risk rank based on RCN, RF and absolute difference between them

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We can conclude that the maximum difference in risks' rank is appeared in risks with low or high value of *CN*. For example, the WFD and IWO risks are the highest important risks based on *RF* and *RCN*. The low value of *RCN* for WFD shows that this risk could be controlled easily in contrast to IWO. Considering *CN* in risk evaluation is more rational than discarding this index because clients deal with IWO risk more than WFD based on our observation and it is more suitable as a high ranked risk.

Another important finding from Figure 11 is related to FUS, having maximum value of difference. Although this risk has a higher importance without consideration of *CN*, the high ability of controlling this risk makes it as a 15th important risk. It could be concluded that by introducing LSF risks and managing them, the main objective of this study, we can reduce the impact of FUS especially in developing countries.

4.7 A pilot study for results' Validation

The methodology was illustrated and validated through its application to the pilot case study once the Fuzzy FMEA model was developed for the identified risks entailing evaluation and responding procedure. The following approach with the aim of the *SED* criteria was applied to validate the solutions for each risk.

A pilot study comprising a two-story LSF residential building in Iran with 220 m² built-up area in design phase with stick's construction method (Yu, 2016) was considered. The WBS, CBS and QBS of this building was designed by the project team brainstorming the construction process suggested by Barnard (2011) and Eren (2013) based on ten phases including Ph1: casting the concrete slab, Ph2: runner and stud's erection, Ph3: screw fixing, Ph4: roof erection, Ph5: Insulation and weatherproofing, Ph6: plumbing and electrical services, Ph7: gypsum board attaching, Ph8: doors and windows installation, Ph9: façade's installation and coating and Ph10: painting. The *SED* calculations in the above project phases are shown in the first row of Table 3. Note that the final quality (the value of quality in for *SED* computation) in the planning state was assumed equal to 1.

Table 3. *SED* calculations in project phases for target state, UEMLMC and FRP response solutions

The WBS chart of the project tasks are shown in Figure 12. The implication of each risk solution(s) based on *SED* was calculated for each phase and the final values of cost, time and quality were determined. Note that the modified values of objective's weights without

714 consideration of safety and environmental issues based on pairwise fuzzy calculation are
715 $W_r=0.24$, $W_c=0.42$ and $W_q=0.34$. The results show that increasing in the *SED* was shown only
716 in one risk. Only two important cases are reported here for brevity.

717

718 Figure 12. WBS chart of the project's tasks

719

720 DFI obtained minimum value of *SED* among all the risks. After removing improper responses
721 to risk strategies, the best solution for this risk (has minimum value of *SED*) is 'using expanded
722 metal lath with white mortar cement (UEMLMC)' instead of dry façade as shown in Figure 13.
723 To use this solution, the expanded metal lath should be screwed to studs and runners (panel (a)
724 and (b) in Figure 13) and then white (or other colours) mortar cement covers all the metal lath
725 and thus a flat white surface will be obtained (panel (c) in Figure 13).

726

727 Figure 13. Panel (a) and (b): Screwing expanded metal lath on studs and runners. Panel (c): Covering white
728 mortar cement on the metal lath

729

730 This solution reduces the façade's cost from \$3,000 to \$1,900 and has no change in the project
731 time because of being parallel with other tasks (based on Figure 12, this task has 6 days buffer).
732 A part of the project QBS is shown in Figure 14 and the quality of the project specification
733 based on the project team opinion is specified without and with consideration of suggested
734 solution (final quality for second condition is $(0.4 + 0.05 + 0.2) \times 0.4 = 0.26$). The *SED*
735 calculations for the project phases considering UEMLMC response solution for the risk event
736 DFI is shown in the second row of Table 3.

737

738 Figure 14. A part of QBS (red values indicate quality with consideration of suggested solution)

739

740 Despite different solutions mentioned by several authors and our experts for FIM ([Jatheeshan](#)
741 [and Mahendran, 2015](#), [Veljkovic and Johansson, 2006](#)), the *SED* values for all these solutions
742 are positive. Among the suggested solutions, fire-resistant plasterboard (FRP) was chosen as
743 the best one with minimum value of *SED* for this risk. Fire resistant gypsum boards are 60%
744 more expensive than normal ones that have effects on project time and quality so the *SED* is
745 nearly equal to 1%.

746 The high value of *RCN* for FIM implies that an applicable preparation should be considered
747 for this risk, but *SED* has no recommendation for a proper solution. The main reason for this

748 inconsistency can be referred to the exclusion of safety in *SED* calculation as a criterion. In
749 other words, the main effect of FRP is on the project safety instead of quality, time and cost.
750 Calculation of *SED* based on safety can be considered for future researches. The *SED* related
751 calculations in terms of project's phases considering FRP response solution for the risk event
752 FIM is shown in the third row of Table 3.

753 Applying the proposed method on the above real case revealed that the selected solutions
754 generally can obtain remarkable validations based on the expert judgments. However, the
755 solutions may need some modifications and justifications in some complicated risks hence
756 considering experts' opinion is highly recommended after implementation of this method.

757 **4.8 The key findings of the study**

758 In this subsection, the findings of this paper are summarised as some practical guidelines. They
759 might be useful in other related cases and problems to prevent any adverse outcomes of the
760 risks. The following key findings can be noted from the application of the methodology in the
761 paper:

- 762 • Based on the PLC classification, the risks in the operation phase are larger than those
763 in the design and construction phases.
- 764 • Only 15% of the identified risks in the construction projects could be accepted.
- 765 • Due to being an environmentally friendly system, decreasing people's unreliable
766 feelings to the LSF system causes expansion of the system and then several
767 environmental benefits.
- 768 • Among non-accepted risks, 3 risks including cracks in the walls, limitation in designing
769 of high-rise buildings and danger of explosion and blast have low probability of
770 occurrence and risk impact, but control ability against them is very limited. Hence,
771 transferring strategy is a reasonable choice for dealing with these risks.
- 772 • Some of the identified risks relating to the average temperature, corrosion and wind
773 force in this study are specific to the region and country of the case study and hence
774 different results may be obtained in other countries.
- 775 • Implementation of dry façade and dry walls may have major challenges and need
776 principal considerations and modifications in the design phase.
- 777 • Construction and operation risks have higher importance than design risks based on the
778 average obtained *RCN*.
- 779 • Investigation of the safety as a criterion in the risk management process can give more
780 acceptable results.

781 ***Conclusions***

782 This paper contributes to the body of knowledge of risk management implementation in the
783 LSF systems by using the Fuzzy FMEA approach. Risk management main process entailing
784 identification, evaluation and response was applied to the design, construction, and operation
785 steps of the LSF system in a pilot study in Iran as a developing country. 29 important risks
786 were extracted through interviewing with people related to the LSF system. The proposed
787 Fuzzy FMEA model considered five criteria entailing cost, quality, time, safety and
788 environmental issues and determined risk magnitude based on three components comprising
789 the control ability of the project team to handling the risk, probability of occurrence and
790 consequence on the project criteria.

791 Results revealed that the share of risks in design, construction and operation steps are 21%,
792 31% and 48% respectively and the construction and operation risks have higher importance
793 than design risks. Also, the cost and quality are the most important criteria in this model
794 according to average of risk magnitude. Using Multiple-Criteria Decision Making (MCDM)
795 under Hesitant fuzzy sets is recommended for identification and risk analysis of sustainable
796 building projects in future works.

797 ***Data Availability Statement***

798 Some or all data including the questionnaire information, fuzzy computations and etc. that
799 support the findings of this study are available from the corresponding author upon reasonable
800 request.

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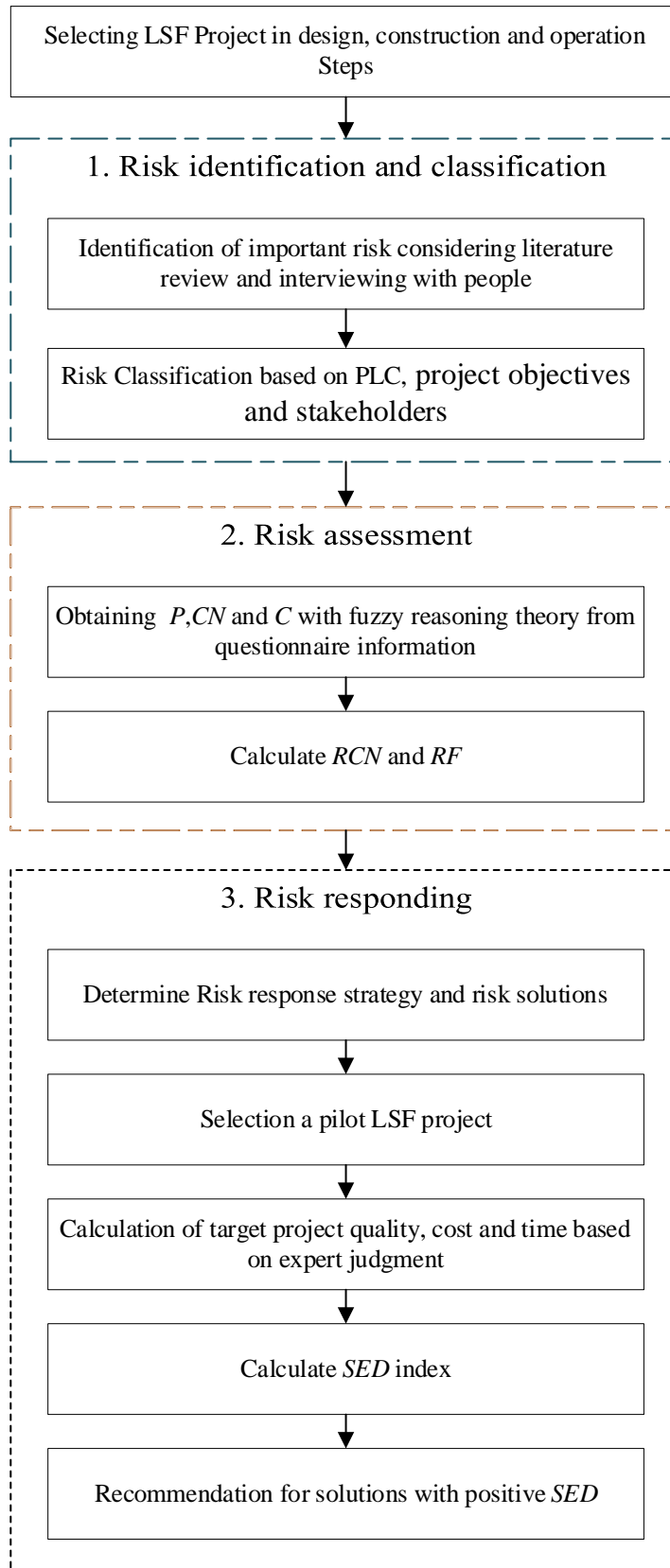
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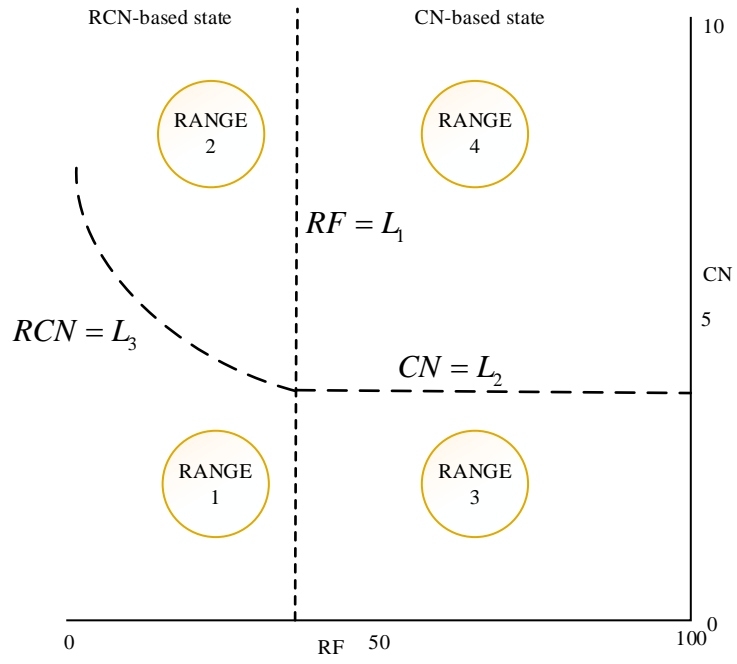
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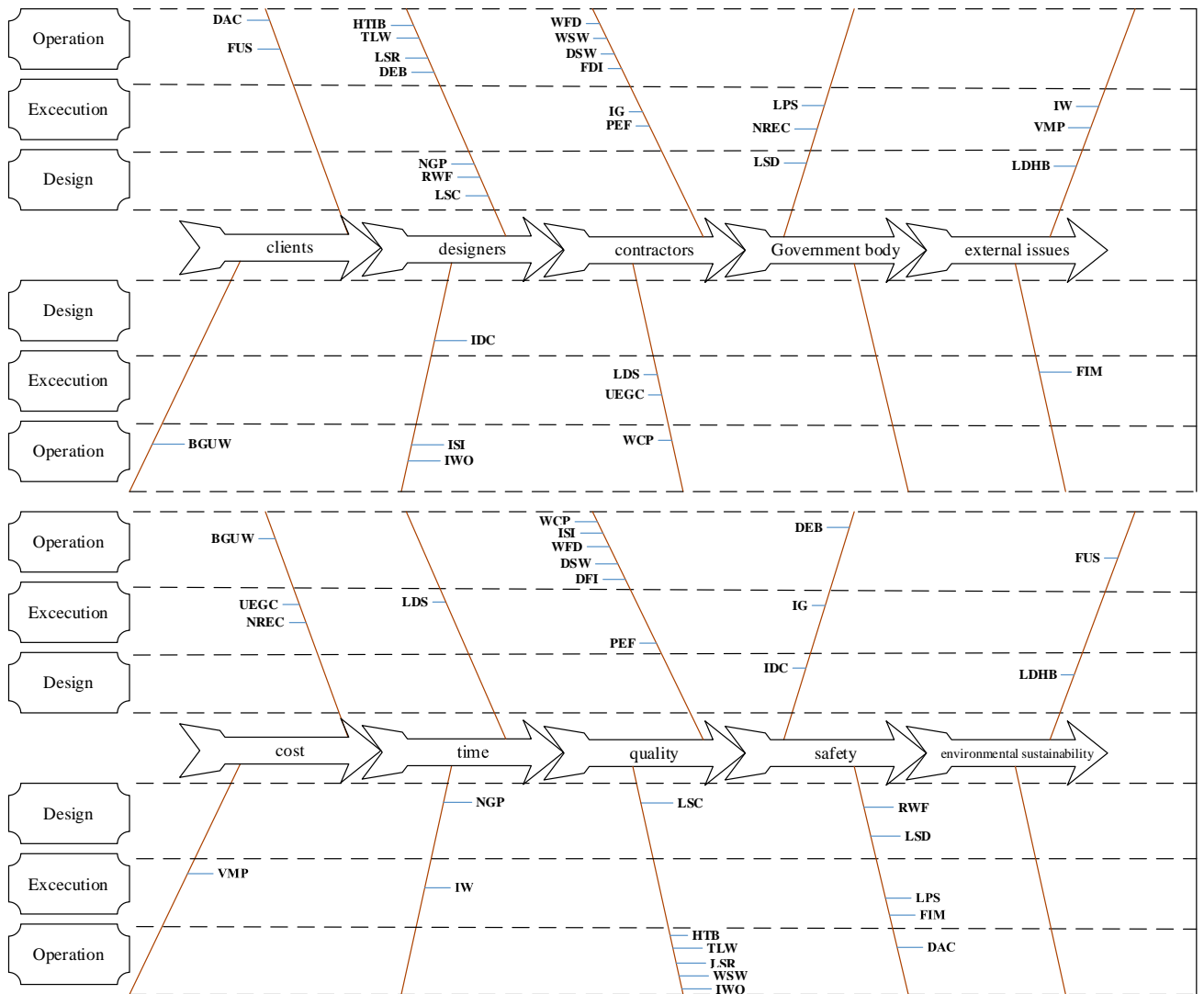
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Figure 15. The methodology flowchart



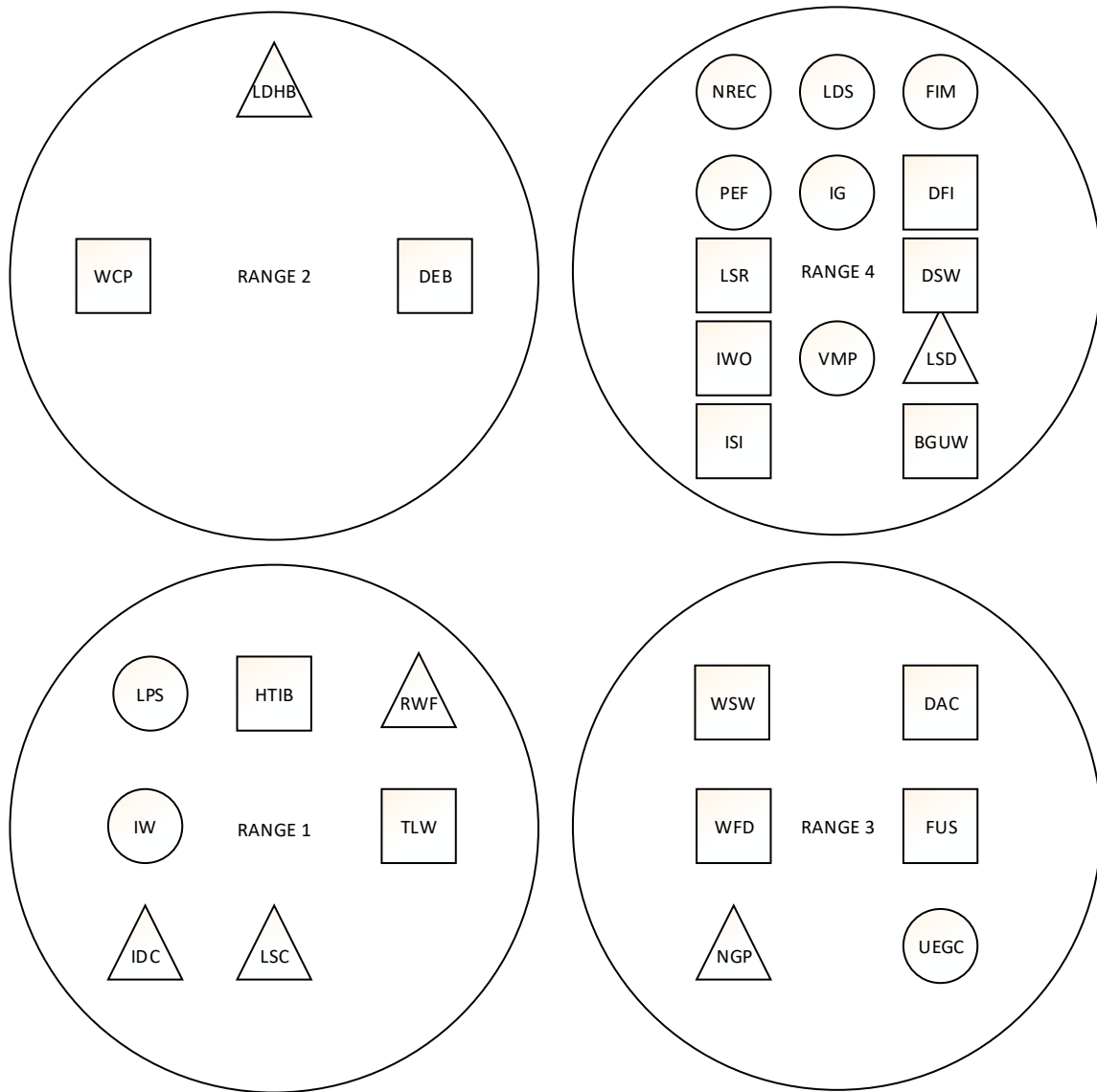
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Figure 16. Selection the risk response strategy based on RCN , CN and RF



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Figure 17: The fishbone diagram in accordance to stakeholder vs PLC (first panel) and objectives vs PLC (second panel)



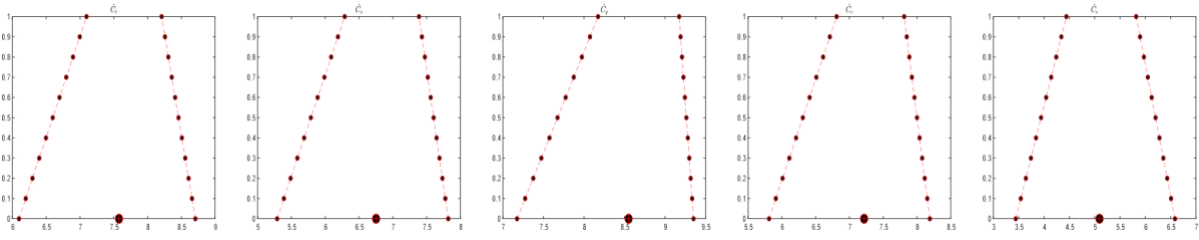
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Figure 18. Assignment of risk response range in term of design (triangular), construction (circle) and operation (square) phase



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Figure 19. Left panel: Combination of LSF system with shear wall in a 7-story school. Right panel: panelization in LSF buildings (Yu, 2016)



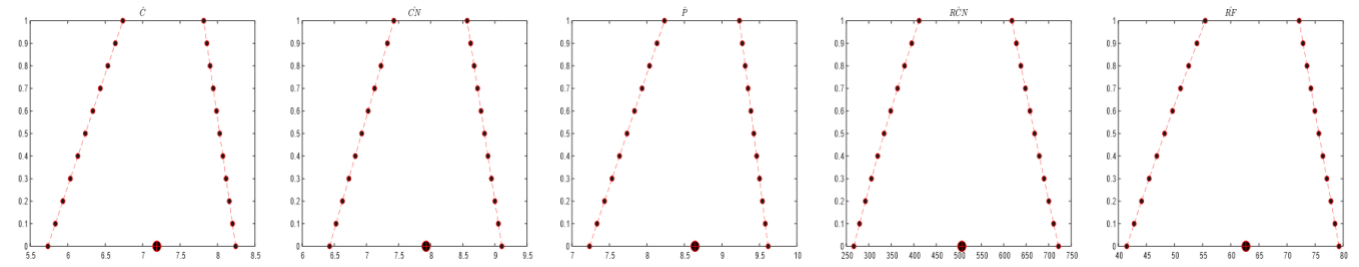
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Figure 20. Fuzzy numbers for consequence of the risk event of IWO related to $\hat{C}_1, \hat{C}_3, \hat{C}_q, \hat{C}_c$ and \hat{C}_e

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respectively



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Figure 21. Fuzzy numbers of $\hat{C}, \hat{CN}, \hat{P}, \hat{RCN}$ and \hat{RF} for IWO



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Figure 22. Dry facades problems in LSF system: right panel: striking some heavy things to dry facades. Left

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panel: bad performance of construction or insulation



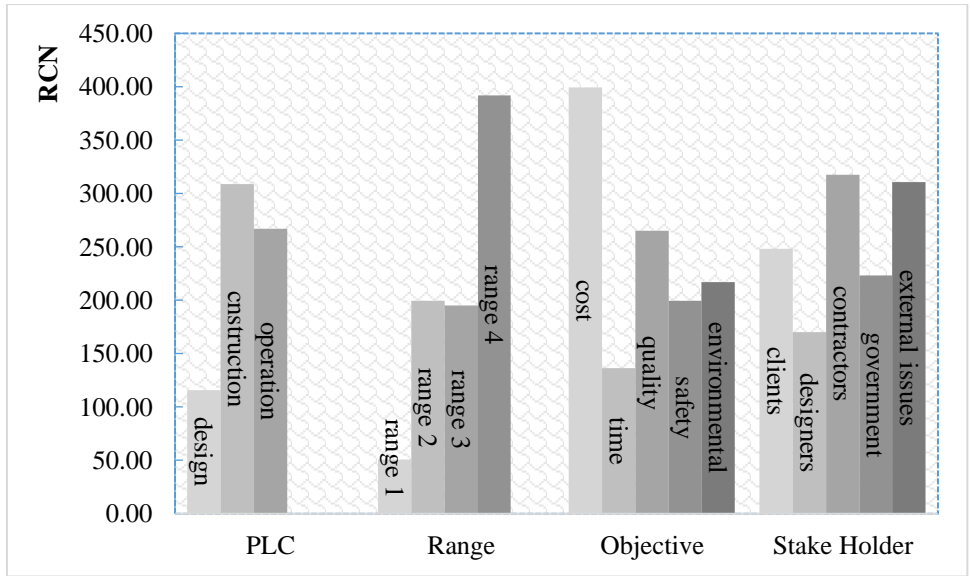
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Figure 23. a: ribbed plastic anchor, b: self-drilling anchor, c: toggle bolts, d: molly bolts and e: marking the

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place of studs

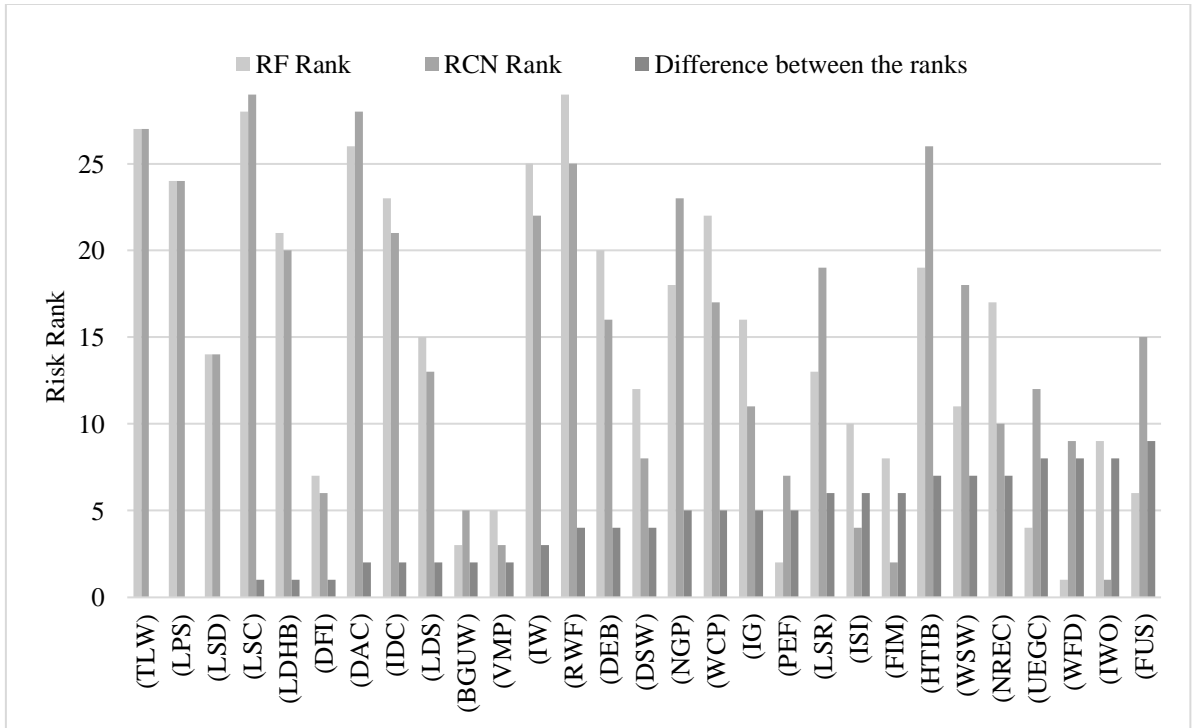


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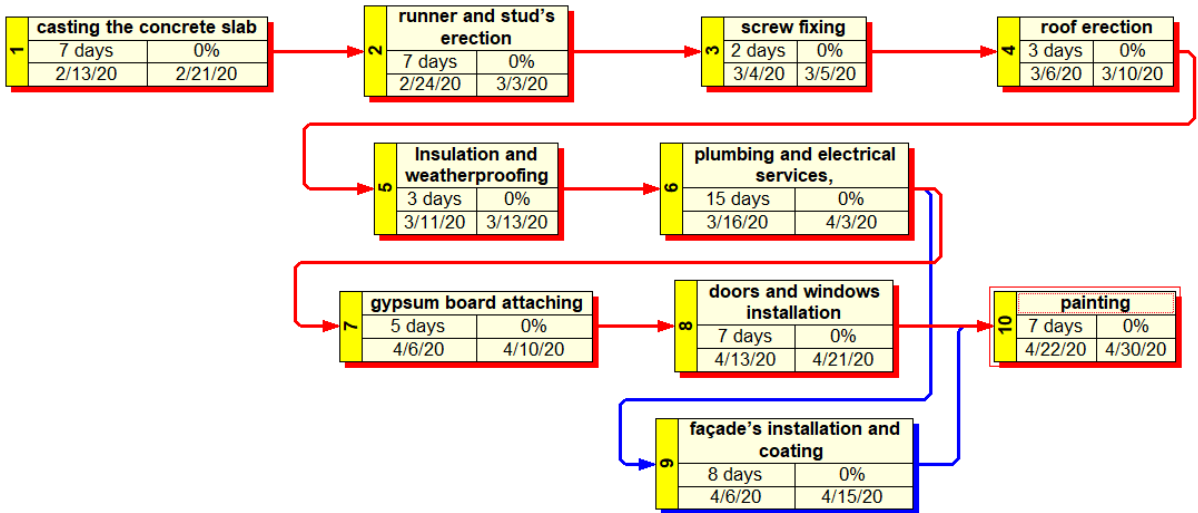
Figure 24. The average RCN of the risks in the PLC, project objective, project stakeholders and risk response range classes



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Figure 25. The risk rank based on RCN, RF and absolute difference between them



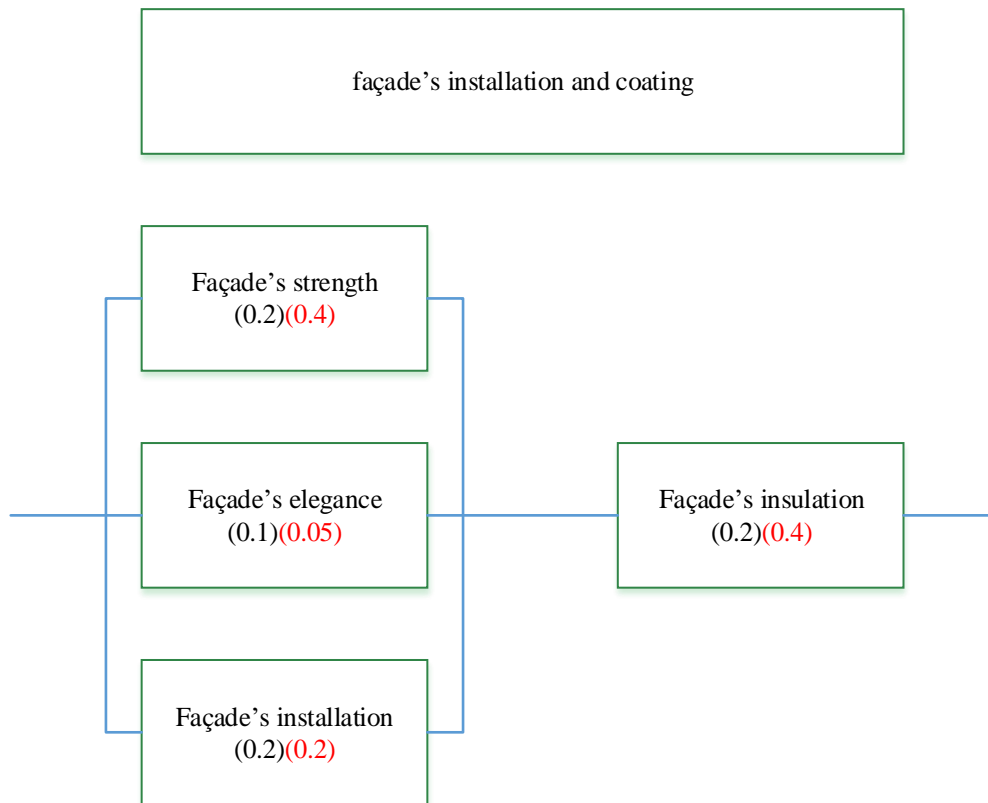
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Figure 26. WBS chart of the project's tasks



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Figure 27. Panel (a) and (b): Screwing expanded metal lath on studs and runners. Panel (c): Covering white mortar cement on the metal lath



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Figure 28. A part of QBS (red values indicate quality with consideration of suggested solution)

Table 4. The structure of the questionnaire

Questionnaire No.	Question	Model parameter	Status
1	The cost, time, quality, safety and environmental issues preference of the LSF projects relative to each other	w_c, w_q, w_t, w_s and w_e	only one questionnaire for all risks
2	The probability of occurrence of risk No. ...	P	replicate for each risk
3-7	The severity of consequence of risk No. on cost, time, quality, safety and environmental issues	C_c, C_t, C_q, C_s and C_e	replicate for each risk
8	The project team control rate for risk No.	CN	replicate for each risk
9	What class do you suggest for of risk No.?	-	replicate for each risk
10	What solution(s) do you suggest for of risk No.?	-	replicate for each risk

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Table 5. Calculating the model’s components for identified risk in the ascending order of RCN

Risk (Acronyms)	Risk Class	RCN	RF	CN	Risk Response Range
Lack of space predicted for desert cooler/ Air conditioner (LSC)	Designing/quality/designers	29.61	9.87	3	1
Durability against corrosion (DAC)	Operation/safety/clients	31.752	13.23	2.4	1
Thickness of load bearing walls (TLW)	Operation/quality/designers	33.696	12.96	2.6	1
High temperature inside the building (HTIB)	Operation/quality/designers	37.584	31.32	1.2	3
Resistance to wind force (RWF)	Designing/safety/designers	37.884	9.02	4.2	1
lack of the professional supervision (LPS)	Construction/safety/government bodies	50.505	13.65	3.7	1
No space predicted for gas pipelines (NGP)	Designing/time/designers	52.864	33.04	1.6	3
Impermanent workforces (IW)	Construction/time/external issues	57.276	13.32	4.3	1
Incompatibility in design and construction of joints (IDC)	Designing/safety/designers	114.66	14.7	7.8	1
The limitation in designing of high-rise buildings (LDHB)	Designing/environmental sustainability/external issues	176.832	28.8	6.14	2
Lack of space for roof stairs (LSR)	Operation/quality/designer	178.704	49.64	3.6	4
Weak sealing of windows (WSW)	Operation/quality/contractors	182.91	52.26	3.5	3
Wall cracks in electric and plumbing pipes’ place (WCP)	Operation/quality/contractors	183.372	24.78	7.4	2
Danger of explosion and blast (DEB)	Operation/safety/designers	238.702	29.11	8.2	2
Feeling of unreliable structure (FUS)	Operation/environmental sustainability/clients	256.62	73.32	3.5	3
Lack of standards for design (LSD)	Designing/safety/government bodies	283.91	48.95	5.8	4
Risk of labor disputes and strikes (LDS)	Construction/time/contractors	299.691	47.57	6.3	4
Rippling surface of wall ceramics (UEGC)	Construction/cost/contractors	303.62	89.3	3.4	3
Improper galvanizing (IG)	Construction/safety/contractors	332.332	40.04	8.3	4
Not-rated executive contractors (NREC)	Construction/cost/government bodies	334.768	34.16	9.8	4
Window’s frame deformation over time (WFD)	Operation/quality/contractors	336.14	96.04	3.5	3
Disturbing sound of expansion and contraction of walls (DSW)	Operation/quality/contractors	389.424	51.24	7.6	4
The problem in construction of flushing (PEF)	Construction/quality/contractors	395.01	94.05	4.2	4
Dry façade's issues (DFI)	Operation/quality /contractors	434.026	64.78	6.7	4
Breakable gypsum-board leading to unreliable walls (BGUW)	Operation/cost/clients	455.7	91.14	5	4
Improper sound insulation (ISI)	Operation/quality/designers	474.24	62.4	7.6	4
Vulnerability to moisture penetration (VMP)	Construction/cost/external issues	502.928	73.96	6.8	4
Flammability of insulation material (FIM)	Construction/safety/external issues	504.972	64.74	7.8	4
Intolerability to install weighted objects (IWO)	Operation/quality/designers	506.202	62.7264	8.07	4

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Table 6. SED calculations in terms of project’s phases for target state, UEMLMC and FRP response solutions

State	Criteria	Ph1	Ph2	Ph3	Ph4	Ph5	Ph6	Ph7	Ph8	Ph9	Ph10	Total project	SED (%)
Target	Time (day)	7	7	2	3	3	15	5	7	8	7	69	-
	Cost (\$)	3000	5500	200	2500	3000	3500	2000	1000	3000	2500	26200	

State	Criteria	Ph1	Ph2	Ph3	Ph4	Ph5	Ph6	Ph7	Ph8	Ph9	Ph10	Total project	SED (%)
UEMLMC	Quality	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1	
	Time (day)	7	7	2	3	3	15	5	7	8	7	69	-7.203
	Cost (\$)	3000	5500	200	2500	3000	3500	2000	1000	1900	2500	25100	
FRP	Quality	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.26	0.1	1.16	
	Time (day)	7	7	2	3	3	15	5	7	8	7	69	0.962
	Cost (\$)	3000	5500	200	2500	3000	3500	2000	1600	3000	2500	26800	
	Quality	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1	

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